MAAP4 UNCERTAINTY AND SENSITIVITY ANALYSES

Uncertainty Working Group of the MAAP User's Group

K. Nagashima (NUPEC), M. Alammar (GPU), H. C. Da Silva (TU), R. E. Henry (FAI),
M. Kenton (D&M), D. Kuhtenia (TE), M. Kwee (OH) and W. Ranvall (EDF)

ABSTRACT

MAAP4 analyses have been performed to investigate the influences of uncertainties in severe accident phenomena. These analyses are coordinated through and reviewed by the MAAP User's Group and reported on at each MAAP User's Group meeting to aid the users in performing IPEs, PRAs and/or accident management studies. The uncertainty approach as described by Nagashima, et al. (1995) divides the physical phenomena into three categories (Table 1), i.e. dominant, significant or minor in their importance to the accident progression, more particularly in an accident management point of view. Each phenomenon is divided into subphenomena for which uncertainty bounds can be quantified through various separate effects experiments. This quantification is documented in a living report such that the evidence of the quantification reflects the most recent experimental data in addition to information previously reported in the literature.

Table 1
Preliminary Assessment Characterization of Severe Accident Physical Phenomena

Phenomena	Dominant	Significant	Minor
1. Clad oxidation.		°	
2. Core melt relocation.		°	
3. Molten pool in core.		°	
4. Crust formation and failure.		°	
5. RCS failure modes.	°		
6. In-vessel steam explosion.			°
7. In-vessel steam generation.			°
8. In-vessel debris formation.			°
9. RPV failure modes.		°	
10. In-vessel cooling mechanism(s).	°		
11. RPV external cooling.	°		
12. Ex-vessel steam explosion.			°
13. Direct containment heating.		°	
14. Mark I liner attack.		°	
15. Ex-vessel debris cooling.	°		
16. Steam inerting of the containment	°		
17. Hydrogen burning in containment.		°	

As discussed by Nagashima, et al. (1995) the in-vessel cooling evaluation found this to be a dominant phenomena since it could prevent RPV failure for sequences in which vessel injection would be recovered within about one to two hours after the core was uncovered.

This initial phenomenological assessment determined that ex-vessel (in-containment) debris cooling was also a dominant phenomenon. This paper presents the application of the uncertainty methodology to ex-vessel debris cooling.

1.0 INTRODUCTION

As addressed by all the PSAs/IPEs performed on nuclear operating plants in the United States, Europe and the Far East, the conditions leading to a severe accident are those with inadequate cooling of the nuclear fuel even after the reactor was shut down. Correspondingly, should an accident occur, it is necessary to cool the debris to stop the accident. During the TMI-2 accident, this occurred as a result of reflooding the reactor vessel and the relocation of tens of tonnes of molten core debris from the reactor core to the core bypass and the RPV lower plenum regions.

As addressed by the plant specific PSAs/IPEs, there is a frequency, although very low, for which severe accidents should occur and the core debris would not be cooling within the vessel, i.e. the reactor vessel would fail and core debris would be released to the containment. Under these conditions, the objectives of accident management actions remain the same, i.e. cool the core debris by submerging it in water. However, the debris cooling rate has significant uncertainties under these conditions.

Cooling of overheated core debris is dependent upon the debris configuration. For example, experiments performed with non-uniform debris sizes show that cooling rates can be reduced as a result of tighter bed "packing". Furthermore, the rate at which debris leaves the reactor coolant system may occur such that the debris accumulates as a continuous layer, which may have a cooling rate substantially less than that for particle beds. Lastly, the dynamics of the accident sequence could influence the location of debris within the containment. Direct Containment Heating (DCH) experiments (Henry et al., 1991; Allen et al., 1994; Binder et al., 1994) demonstrate that debris discharged into a reactor cavity, with the RCS pressurized, could be dispersed onto the containment floor. A dispersed debris configuration could also be caused by ex-vessel steam explosions in the reactor cavity/pedestal. In general, dispersing core debris over the containment floor enhances the cooling rate.

Debris bed models for one-dimensional, countercurrent coolant flow were surveyed (Lipinski, 1980; Ostensen, 1979; Hardee and Nilson, 1977; Dihr and Catton, 1976; Henry and Fauske, 1981; IDCOR, 1983) as part of this ex-vessel cooling uncertainty evaluation. Typically, the particle sizes resulting from DCH experiments would experience heat removal rates of 0.1 to 1.0 MW/m^2 of projected area based on uniform sized particles. However, those conditions in which debris has been dispersed also result in a substantial increase in the projected area to 100 m^2 or greater. This also results in a thinner debris depth such that thermal conduction is more influential. Therefore, with these conditions, quenching of the core material and decay heat removal is virtually assured if the debris is submerged in water. Furthermore, dispersal of the core debris over a large area increases the energy that could be removed by thermal conduction. Thus, there is little uncertainty related to the extent of cooling for dispersed debris.

As an additional note on the cooling of particulated debris, evaluations have been made with respect to the two-dimensional, two-phase cooling process. It has been found that two-dimensional cooling of particulated debris increases the heat removal rate by approximately a factor of two (IDCOR, 1983; Catton and Chung, 1994). Therefore, using a one-dimensional approach is conservative, but this approach generally results in conditions in which the debris could be cooled because of the large area over which debris could be distributed (CECo, 1981). (Note that the smaller the particles the greater the potential for dispersal over a larger area.)

With the survey of the debris bed behaviors, it can be concluded that the combination of dispersed core material over a larger region, thermal conduction and the two-dimensional cooling, all represent effects which reduce the importance of uncertainties associated with the particle size distribution and the particle arrangement in the bed. Thus, the major configuration of concern is one where the debris accumulates as a continuous layer in a containment compartment, i.e. the reactor cavity (PWR) or pedestal (BWR) regions. With such an accumulation, core debris quenching requires cooling by the overlying water pool. This is the configuration with the least amount of experimental evidence and the greatest uncertainties in the cooling rate.

2.0 TECHNICAL BASIS FOR COOLING OF A CONTINUOUS CORE DEBRIS LAYER

Cooling by an overlying water pool focuses on the potential for water ingression into (1) cracks developed as the debris crust quenches, and (b) “blow holes” created if the core material attacks the concrete substrate, thereby causing additional gas release. The available technical basis for such conditions come from relatively small experiments (Malinvoic et al., 1989), the MACE tests (Spencer et al., 1989; Spencer et al., 1992 and Farmer et al., 1992) and observations of quenching lava by surface spraying (Bjornsson et al., 1982) at the Gromsvotn lava flow. It is noted that small scaled SWISS experiments (Blose et al., 1987), performed with molten stainless steel, while technically interesting, are not applicable to this particular assessment since the high internal heat generation created a state where both the film boiling radiative heat loss from the upper surface and the upper surface cooling by water ingression (about 1 MW/m^2) result in a heat flux in which the debris could not be quenched. Moreover, both (an assumed porous bed and a non-porous bed) yield virtually the same heat flux such that the more appropriate modeling approach cannot be discriminated by the data.

If the debris is formed as a continuous layer, part of which may be molten and part a solid crust, and is not sufficiently cooled, the internal heat generation within the core material will eventually overheat the concrete and/or the containment liner, depending upon the configuration, and initiate core-concrete attack. To prevent such attack, the core debris/containment wall interface temperature should remain below approximately 600°C, otherwise, concrete decomposition would likely occur.

Heat removal occurs by thermal conduction through the debris continuum as well as by water ingression into the debris through cracks and crevices developed as a result of the freezing process. We first approximate heat removal by conduction from the debris to the debris-concrete interface and then address the more complex issue of water ingression.

Heat removal by steady-state conduction can be expressed as

$$\Delta T = \frac{\dot{q}_v L^2}{2 k_c} \qquad (1)$$

where L is the thickness of the debris layer and k_c is the debris thermal conductivity. Considering that the core material upper surface is at 100°C (boiling), a temperature difference of 500°C is available for conduction, while still preventing temperatures greater then 600°C at the debris-concrete interface. With a volumetric heat generation rate of 1 to 2 MW/m^3, one calculates a core material thickness of 8 and 4 cm respectively. Hence, for thicker debris configurations the interface temperature would be sufficient to cause concrete decomposition. (In this simplified analysis we have neglected conduction into the concrete substrate. While this is clearly a simplifying assumption, over the long term, this conduction into concrete becomes increasingly less important as the concrete thermal boundary layer grows thicker.)

Water ingression is a means whereby the heat removal can be substantially increased over and above that removed by conduction. Figure 1 illustrates water ingression and the associated temperature profiles. The top figure shows water ingressing into a solidified crust and cooling debris to essentially water saturation. If this process is extremely effective, all the debris could be cooled by water ingression. Possible filling of the cooling paths by precipitated boron (reducing the cooling potential) is also illustrated and is an uncertainty to be considered for ex-vessel cooling.

Small scale experiments (Malinovic et al., 1989) show quenching rates of approximately 30 MW/m^2 when the debris was molten and about 0.5 MW/m^2 after the debris upper surface has solidified (see Figure 2). The lower value is sufficient to remove decay heat and quench the debris to the water saturation temperature which would also cool the concrete substrate to these temperatures, i.e. the containment integrity would be preserved. These measurements are part of the technical basis to be evaluated when assessing ex-vessel debris cooling.

The MACE experiments were designed to create a molten debris pool, using uranium dioxide in contact with the concrete, and initiate thermal attack of the concrete walls when the debris is submerged in water. As discussed by Spencer et al. (1992), the smaller scale MACE scoping test accomplished all of these objectives and the following M1 test accomplished most of the objectives. In addition, the MACE test M1B (Farmer et al., 1992) achieved these test objectives. All of the experiments found that the melt-water interaction is highly transient, with the initial melt-water interaction being very vigorous and having a heat removal rate of as much as 3.5 MW/m^2 (MACE scoping test). Furthermore, for the MACE test M1B, it was observed that the melt-water heat removal "was well in excess of saturated water CHF for a long time interval following water addition". Moreover, all of the MACE experiments observed transient

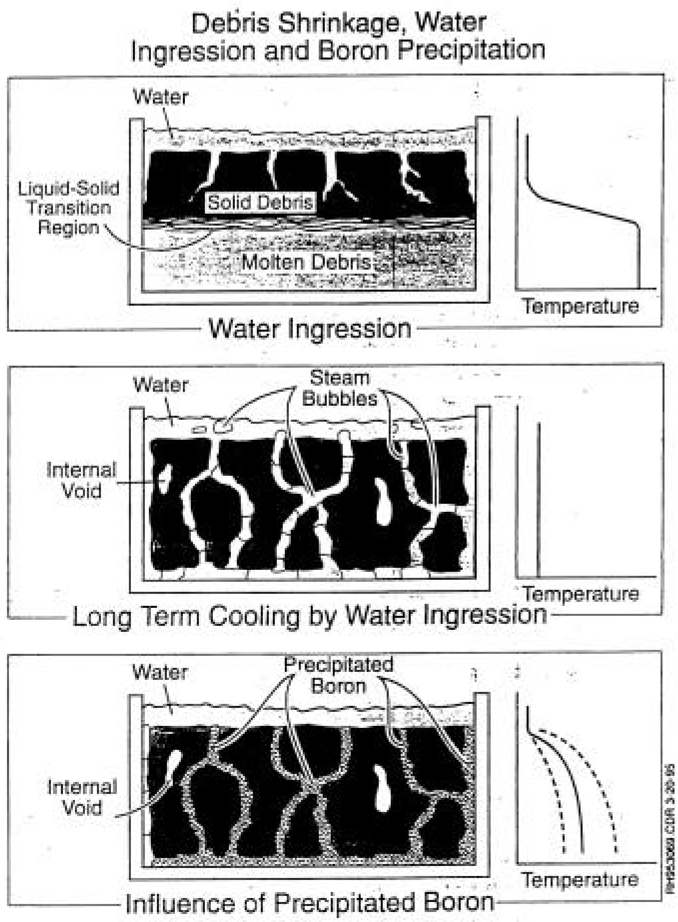

Figure 1

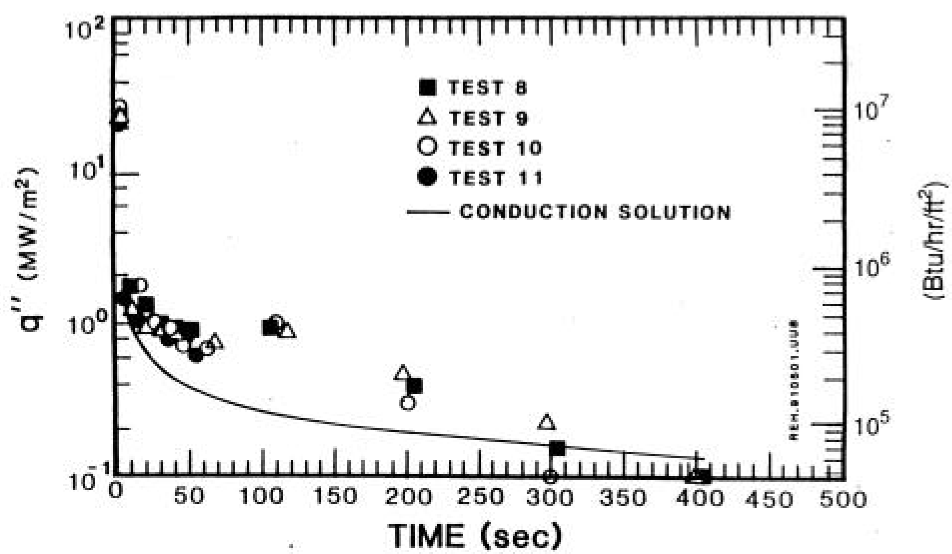

Figure 2, Comparison of the calculated heat fluxes for EPRI Tests 8, 9, 10 and 11 and which could be removed by conduction. (Source: Malinovic et al., 1989.)

ejection of melt into the overlying water pool that contributed both to the debris-water heat removal as well as changes in the debris configuration. As a result of the significant energy transfer, the rate of concrete ablation was reduced by an order of magnitude in the MACE M1B test. Hence, these results illustrate that an overlying water pool can be effective in cooling the core debris and substantially mitigating the rate of core-concrete attack and, potentially, even eliminate such attack. These results are clearly part of the technical basis to be used in assessing the role of uncertainties in ex-vessel debris coolability.

The results of the MACE experiments were evaluated by Epstein (1992) and provided time dependent behaviors in which eruptions occurred from a crust and resulted in greatly increased heat removal from the core material. As discussed by Epstein, during these periods of eruption, the heat removal rate was approximately 1.8 Mw/m^2, while during the times of quiescence the heat fluxes were in the range of 0.15 to 0.5 Mw/m^2. Comparing these results with those observed by Malinovic et al. (1989) in the Mark I liner experiment, it is interesting to note that the heat removal rates during the eruption period are similar to those observed when the melt was being frozen, while those during the quiescent period are comparable to those late in the cooling transient. The cycle time between these two different behaviors in the MACE test was in the range of twelve minutes, a much longer time than that used for the Mark I liner experiments and also a long time for conduction energy transfer. Hence, there is some indication that water ingression could have also been a part of the MACE test since the measured heat removal rates are much greater than conduction in the debris.

Conversely, the Grimsvotn lava field experience showed that water injection at a single location spread over a large area. Specifically, 100 kg/sec of water was sprayed at a single location and was observed to spread over 7000 m^2 of the lava field. After fourteen days, the solidification was measured to have penetrated 12 m downward, or an average rate of 0.9 m/day. This is far faster than could be justified by thermal conduction. Consequently, water ingression was the only reason for this enhanced cooling. Moreover, the quenched lava was observed to be highly fractured with typical dimensions of the resulting particulate being 10 to 20 cm. Temperature measurements near the solidification front showed this strong temperature decrease occurred over a length much less than a meter (~ 0.1 m), indicating the actual cooling and fracturing process took place within a relatively short length. Obviously, the fractured behavior and the water ingression are closely related.

With the measured area coverage and the downward penetration rate, an average heat flux of approximately 40 kW/m^2 is calculated. One could view this result as if water ingression (downward propagation) is limited to 40 kW/m^2 and the imposed spray flow rate (100 kg/sec) spread over an area sufficient to vaporize the imposed water flow. As a first approximation, consider the water ingression capabilities for core debris to be similar to those of lava, i.e. the heat removal capabilities are approximately 40 kW/m^2. With a volumetric heat generation of 1 MW/m^3, a thickness of 4 cm would result in sufficient debris to provide a 40 kW/m^2 at the top of the debris bed. This is a small contribution to the heat removal for thick debris layers.

While the energy balance associated with the lava quenching over this large area is consistent, the fundamental question to be addressed is why did the spray spread over such a large area? One appropriate answer is that the water ingression rate was not sufficient to consume the water spray until it had spread over this large area. If this is the case, the rate at which quenching is observed is approximately 40,000 W/m^2. With this rate, decay heat would not be removed from the submerged core debris, i.e. the debris would not be quenched and containment integrity could eventually be challenged.

Including the Grimsvotn experiment implies an important assumption has been made, namely that the fracture (cracking) behavior of core debris is similar to that of lava. However this also represents the only large scale, unambiguous demonstration of water ingression. As discussed for in-vessel cooling (Nagashima et al., 1995), the TMI-2 lower head overheating and cooling may be explained by water ingression or by a limited wall strain model. As a consequence, one can only assess the average heat flux typical of debris quenching and look elsewhere to confirmation. The TMI-2 results cannot be used to evaluate water ingression rate for core debris. The lava results should be considered as one of the uncertainty bounds related to water ingression.

Water ingression has been demonstrated to occur in the freezing of oxidic materials. The question related to uncertainties in accident analyses is in whether this ingression is of sufficient magnitude to remove the decay heat generated within the core debris. Of particular interest in this context is that all materials shrink as they freeze and cool. This shrinkage induces voids into the material and these voids may, or may not, be interconnected. Those connected provide for a means of water ingression into the bulk of the solidified material, but those not connected do not enable water ingression and slow the thermal conduction energy transfer to the debris boundaries. Both processes occur in any material; the pertinent question is, what is the extent of interconnected voids and how do they influence the overall cooling.

3.0 QUANTIFICATION OF THE UNCERTAINTIES FOR EX-VESSEL COOLING

The major uncertainties to be addressed in integral assessments are:

- particle size if the debris is particulated,
- the particle size distribution or debris bed permeability if significant particulation has occurred,
- the extent of water ingression into a continuous debris layer, and
- the behavior of dissolved materials in the water.

Uncertainties related to the debris particle size are the easiest to address. Relevant experience in the TMI-2 accident, specifically particulated debris in the reactor vessel lower plenum, was that debris had characteristic dimensions from coffee ground size to centimeters (Russell and McCardell, 1989). With the larger sizes, the coolability of the debris would not be limited by the size of the characteristic particle. However, the debris bed cooling rate could be reduced as a result of a non-uniform particle size distribution. Certainly the TMI-2 particulated debris was coolable, yet the cooling rate cannot be determined from the available information.

Another sequence specific issue is whether water in the reactor cavity could be displaced by an ex-vessel steam explosion with a limited quantity of molten material. While the water is displaced, the remainder of the debris could be discharged from the RPV and accumulate in the reactor cavity/pedestal region. Of these, the dispersed debris would be cooled if covered by water because of its limited thickness.

That configuration which has the greatest uncertainty in long term cooling is a continuous material layer (greater than 10 cm), which is formed in the reactor cavity/pedestal region and then submerged by water. In this context, the two major issues related to debris cooling are (1) water ingression and (2) the potential that gases evolving from core-concrete attack could break up the core material causing particulation, thereby forming a debris bed. (The MACE tests observed several eruptions in which molten debris was pushed through the top crust.) For this configuration, there is far less experimental information to draw upon than was the case for particulated debris. While some experiments have been performed, they are limited in number and scale (size) and also involve other nonprototypicalities that make the issues of water ingression and particulation from evolving gases difficult to resolve. Hence, this issue becomes one of the greatest uncertainties to be assessed for those sequences which could progress to RPV failure. Analyses of long term cooling of relatively thick continuous debris layers necessitates using the uncertainty limits for water ingression and debris particulation. For the case of no debris particulation, the limited data suggests that the evaluations must consider the Grimsvotn experience as well as the information from the Mark I liner and MACE tests, i.e. surface heat fluxes could vary from 40,000 W/m^2 to about 1,000,000 W/m^2. For most accident sequences this means that the debris would be analyzed as if it was coolable and not coolable. Such analyses are easily performed using the MAAP code with the parameter (FCHF) representing the combined behavior for particulated core debris and for water ingression. For the heat fluxes given above, derived from experiments and experience at one atmosphere, the value of FCHF should be varied from 0.0036 (40,000 W/m^2) to 0.1 (1,000,000 W/m^2).

4.0 MAAP4 UNCERTAINTY ANALYSES FOR EX-VESSEL COOLING

BWR and PWR reference designs are analyzed using both high pressure and low pressure sequences. The PWR high pressure sequence was a station blackout hot leg creep rupture "ruled out", which is a sensitivity analysis since a phenomenon is "deleted". This is a convenient means of showing the influence of debris dispersal within the containment and its influence on both debris cooling and core-concrete attack. A low pressure sequence was created by evaluating a station blackout scenario (TMLB) with hot leg creep rupture, resulting in complete depressurization of the RCS before reactor vessel failure occurs. There is no dispersal of core debris from the reactor cavity region. For both sequences the containment sprays were recovered after RPV failure to submerge the core debris and evaluate the uncertainties related to ex-vessel cooling.

The BWR sequences selected were (1) a station blackout for the high pressure scenario and (2) a large LOCA for the low pressure case. Here again, the drywell sprays were recovered to submerge the core debris and test the uncertainties in the ex-vessel cooling model. For the station blackout sequence, the containment sprays were recovered at 30,000 seconds and for the large LOCA at 20,000 seconds, which is approximately 15,000 seconds and 10,000 seconds after RPV failure respectively.

Figures 3 and 4 are the respective summary figures of the PWR sequences with the cooling initiated by recovering the containment sprays at 30,000 secs. Several things are to be noted: First, with the three values shown, the sequence without hot leg creep rupture exhibits significant concrete attack only when the parameter FCHF is equal to the lower bound of the uncertainty range, i.e. 0.0036. This is due to the distribution of core material at the time of RPV failure, with approximately 40,000 kg of debris being relocated out of the reactor cavity region, and the remaining core inventory eventually melting and draining into the reactor cavity. For this condition, the debris depth in the cavity is about 0.15 m. For the high pressure scenario, the rate of concrete attack is approximately 6 cm/hr for the lower limit of water ingression with no significant concrete ablation for the other two cases examined.

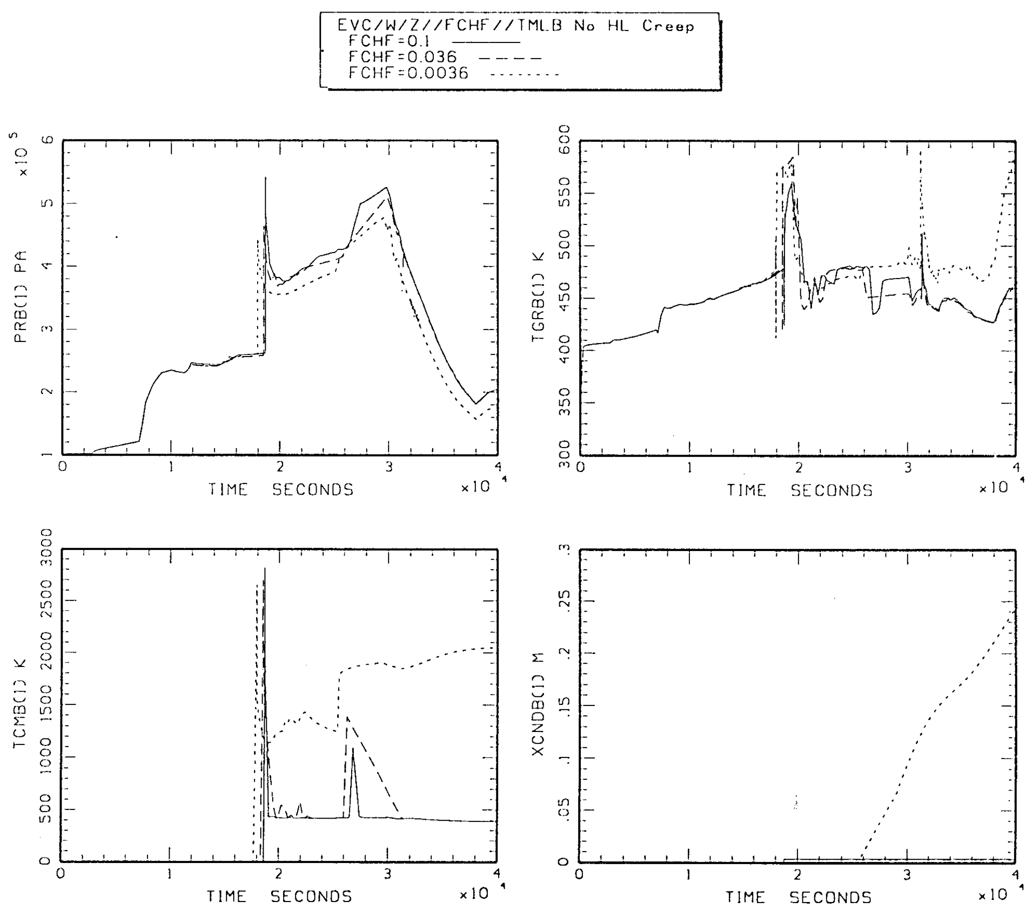

Figure 3

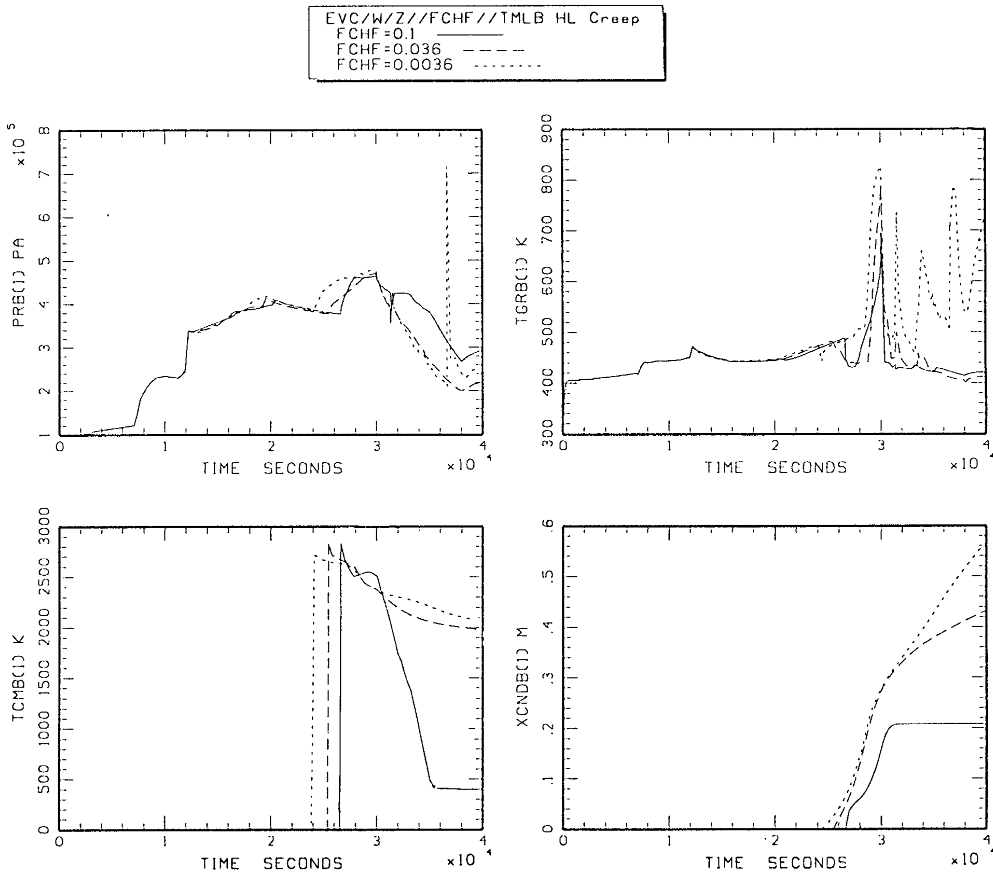

Figure 4

For the lower pressure sequence (with hot leg creep rupture) the debris depth is about 0.25 m and there is significant concrete attack before the sprays are initiated at 30,000 seconds. This increased thermal attack is due to the greater mass of core material in the reactor cavity for this sequence. (Since the reactor coolant system is depressurized to the containment at the time of RPV failure, there is no dispersal of debris out of this region.) Consequently, the entire core mass and the corresponding decay heat, as well as the chemical energy released by oxidation of metals in the core material, is generated within this region and overheats the concrete causing thermal attack. When the sprays are initiated at 30,000 seconds, the water ingression rate represented by FCHF equal to 0.1 is sufficient to immediately quench the core debris and stop the concrete attack. For a value of 0.036, the concrete attack is slowed when the sprays are initiated but core-concrete attack still continues at 40,000 seconds. For an order of magnitude less (0.0036), the concrete attack rate is not substantially decreased as a result of recovering the containment sprays. It should also be noted that, in this case, a hydrogen burn is initiated at approximately 36,000 seconds, causing the containment pressure to increase from 0.2 MPa to 0.72 MPa. Thus, these calculations demonstrate that continued spraying of the containment atmosphere can deinert the atmosphere and initiate combustion of the hydrogen and carbon monoxide, causing a substantial pressurization of the containment.

Figure 5 summarizes the integral response for the BWR analyses with variations in the FCHF parameter again of 0.1, 0.036 and 0.0036. For the largest water ingression rate (0.1), the initiation of containment sprays is sufficient to stop the concrete attack almost immediately. For 0.036, the rate of concrete attack is slowed as soon as the sprays are initiated but continues for the 10,000 second interval investigated in the uncertainty analyses. As was the case with the PWR analyses, a value of 0.0036 for the water ingression rate has only a minor influence on the thermal attack of the concrete; it slows the ablation rate slightly. Since this is an inerted containment, there are no possibilities for initiating hydrogen combustion for these conditions.

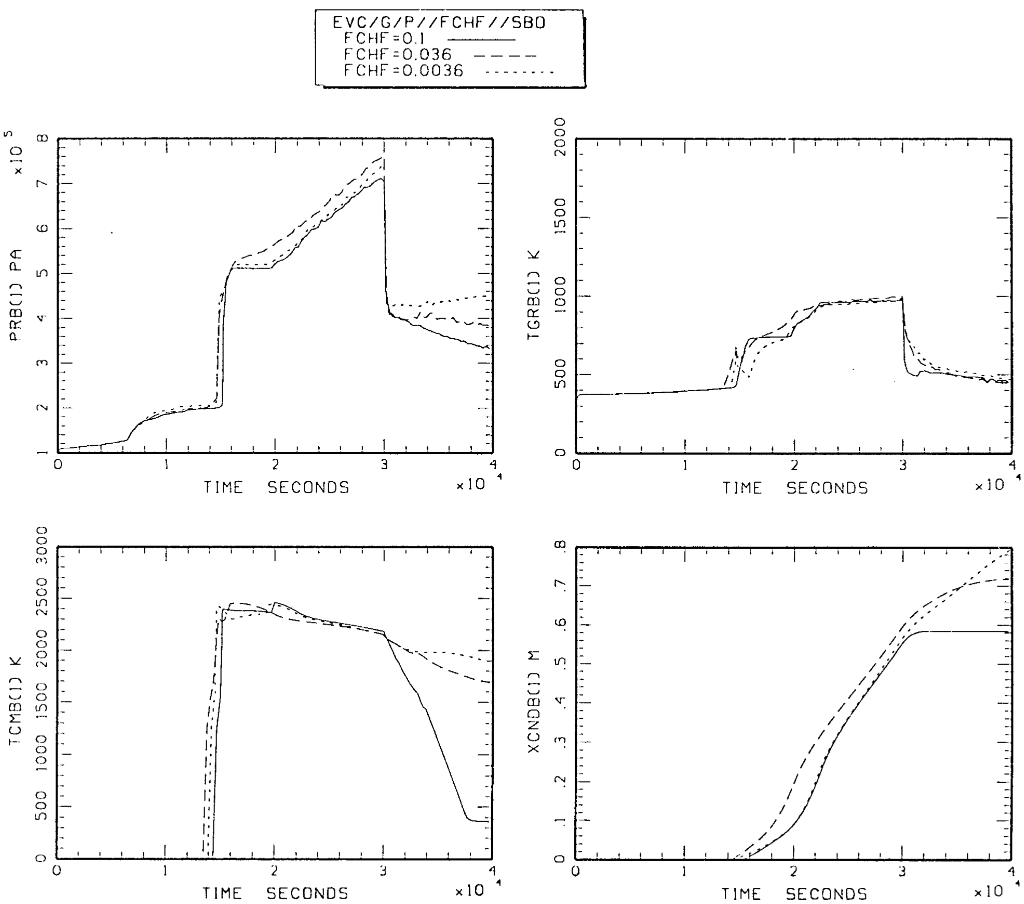

Figure 5

Figure 6 illustrates the integral BWR results for a large LOCA with vessel failure occurring at approximately 9,000 seconds and the sprays being initiated at 20,000 seconds. For the same three characterizations of water ingression rate we find the same substantial variation in the influence on concrete attack, i.e. from immediately stopping the attack to a condition in which there is almost no mitigation of the thermal attack. These results are consistent with the PWR analyses.

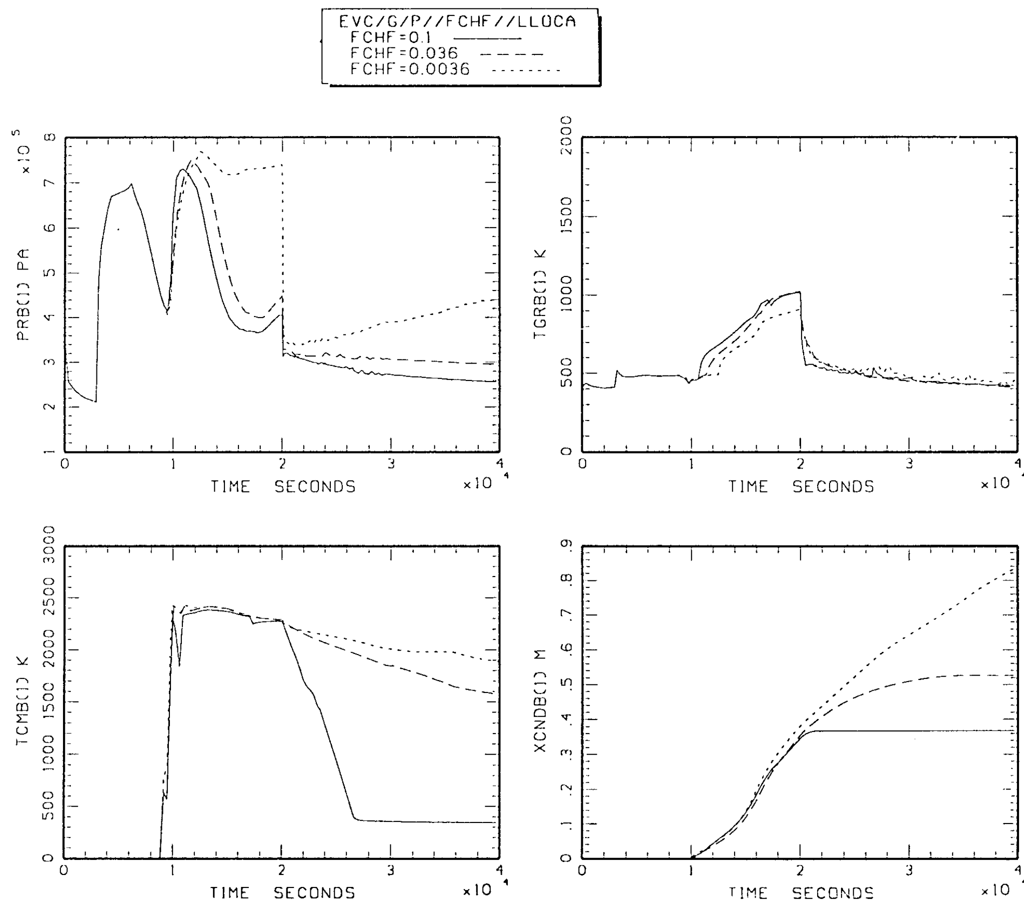

Figure 6

With these integral results, we find that the uncertainties related to water ingression significantly influence the overall accident progression. For the highest water ingression rate, the onset of containment sprays are sufficient to terminate concrete attack and create a safe stable state where the core debris is cooled and there is no continuing attack of the surrounding structures. (Note that sprays may also deinert the containment atmosphere and accelerate the burning rate.) Conversely, for the lower uncertainty value of the water ingression, a rate consistent with the Grimsvotn lava field experience, the containment sprays are not sufficient to stop the thermal attack. Hence, while they will cool the containment atmosphere and scrub fission products that would be released as a result of the core-concrete attack, the surrounding structures would still be attacked as a result of the internal heat generation in the debris. Thus, a safe stable state is not created in this part of the uncertainty spectrum.

5.0 CONCLUSIONS

Evaluations of ex-vessel cooling behavior shows a substantial variation in the cooling behavior depending on the sequence and the process of water ingression. Specifically, reactor safety experiments, as well as other experience related to quenching of high temperature oxidic materials, show that there could be an order of magnitude variation in the water ingression rate.

Utilization of the upper and lower uncertainty bounds related to water ingression generally results in a difference between a mass of core debris effectively cooled by an overlying water pool and one not effectively cooled. In the latter case, substantial core-concrete attack occurs causing pressurization of the containment atmosphere from noncondensible gases and the thermal attack of the containment basemat. It is noted that the extensive concrete attack can also result in the accumulation of large quantities of combustible gases in the containment atmosphere that can significantly pressurize the containment due to a global burn. Therefore, there are other issues associated with this spectrum of uncertainties and can be important in assessing the overall containment response. Considering the difficulty of doing experiments on ex-vessel debris coolability and the considerations of the experimental scale, it is likely that the uncertainties used in the ex-vessel cooling analyses will not be substantially narrowed in the near future. It should also be noted that regardless of the spectrum of uncertainties for ex-vessel cooling, covering the debris with water, should such a state occur, would always be the appropriate action since this cools the containment atmosphere, cools the core debris while scrubbing any fission products released from the debris as a result of core-concrete attack.

REFERENCES

Allen, M. D. et al., 1994, "Experiments to Investigate Direct Containment Heating Phenomena With Scaled Models of Zion Nuclear Power Plant in the SURTSEY Test Facility," Sandia National Laboratory Report NUREG/CR-6044.

Binder, J. L., McUmber, L. M. and Spencer, B. W., 1994, "Direct Containment Heating Integral Effects Tests at 1/40 Scale in Zion Nuclear Power Plant Geometry," NUREG/CR-6168 prepared by Argonne National Laboratory.

Bjornsson, H., Bjornsson, S and Sigurgeirsson, Th., 1982, "Penetration of Water Into Hot Rock Boundaries of Magma at Grimsvotn," Nature, Volume 295, pp. 580-581.

Blose, R. E. et al., 1987, "SWISS: Sustained Heated Metallic Melt/Concrete Interactions With Overlying Water Pools," NUREG/CR-4727, SAND85-1546.

Catton, I and Chung, M., 1994, "Two-Phase Flow in Porous Media with Phase Change: Post Dryout Heat Transfer and Steam Injection," Nuclear Engineering & Design, 151, pp. 185-202.

Commonwealth Edison Company (CECo), 1981, "Zion Probabilistic Safety Study," Commonwealth Edison Report submitted to the U.S. Nuclear Regulatory Commission.

Dhir, V. K. and Catton, I., 1976, "Prediction of Dryout Heat Fluxes in Beds of Volumetrically Heated Particles," Proceedings International Meeting on Fast Reactor Safety and Related Physics, Chicago, Illinois, Volume IV, pp. 2026-2035.

Epstein, M., 1992, "The MACE Internally-Heated Corium-Pool: Was It a Thermal Oscillator?" Paper Presented at The National Heat Transfer Conference, San Diego, California.

Farmer, M. T., Spencer, B. W. and Sehgal, B. R., 1992, “MACE Core Coolability Test M1B,” 20th Water Reactor Safety Meeting, Bethesda, MD, October 21-23.

Hardee, H. C. and Nilson, R. H., 1977, “Natural Convection in Porous Media With Heat Generation,” Nuclear Science and Engineering, 63, pp. 119-132.

Henry, R. E. and Fauske, H. K., 1981, “Core Melt Progression and the Attainment of a Permeably Coolable State,” Proceedings ANS/ENS Topical Meeting on Reactor Safety Aspects of Fuel Behavior, Sun Valley, Idaho, Volume 2, pp. 481-495.

Henry, R. E., Hammersley, R. J. and Klopp, G. T., 1991, “Direct Containment Heating Experiments in a Zion-like Geometry,” AIChE Symposium Series, Volume 87, No. 293, Heat Transfer – Minneapolis 1991, pp. 86-98.

IDCOR, 1983a, “Debris Coolability, Vessel Penetration and Debris Dispersal,” IDCOR Technical Report 15.2B.

Lipinski, 1980, “Particle Bed Dryout Model With Upward and Downward Boiling,” Transactions of ANS, 535, pp. 358-360.

Malinovic, B., Henry, R. E. and Sehgal, B. R., 1989, “Experiments Relating to Drywell Shell-Core Debris Interaction,” AIChE Symposium Series, Heat Transfer – Philadelphia, 1989, Volume 85, No. 269, pp. 217-222.

Nagashima, K. et al., 1995, “Formulation and Use of Uncertainty and Sensitivity Analyses,” Proceedings of the PSA’95 Meeting, Seoul, Korea.

Ostensen, R. W., 1980, “Advanced Reactor Safety Research Program Quarterly Report: October-December, 1979,” Sandia National Laboratory Report.

Russell, M. L. and McCardell, R. K., 1989, “Three-Mile Island Unit 2 Core Geometry,” Nuclear Technology, Volume 87, pp. 865-874.

Spencer, B. W., Sehgal, B. R. and Rahn, R. J., 1989, “Melt Attack and Coolability Experiments (MACE) Program Elements and Scoping Test,” Presentation at the 17th Water Reactor Safety Information Meeting, Washington, D. C.

Spencer, B. W., Farmer, M. T., Armstrong, D. R., Kilsdonk, D. J., Aeschlimann, R. W. and Fisher, M., 1992, “Results of MACE Tests M0 and M1,” Proceedings of the 2nd CSNI Specialist Meeting on Core Debris Interactions With Concrete, Karlsruhe, FRG, April 1-3.